BOUNDARY-LAYER SEPARATION CONTROL UNDER LOW-PRESSURE-TURBINE CONDITIONS USING GLOW-DISCHARGE PLASMA ACTUATORS

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Modern low-pressure turbines, in general, utilize highly loaded airfoils in an effort to improve efficiency and to lower the number of airfoils needed. Typically, the airfoil boundary layers are turbulent and fully attached at takeoff conditions, whereas a substantial fraction of the boundary layers on the airfoils may be transitional at cruise conditions due to the change of density with altitude.[1] The strong adverse pressure gradients on the suction side of these airfoils can lead to boundary-layer separation at the latter low Reynolds number conditions. Large separation bubbles, particularly those which fail to reattach, cause a significant degradation of engine efficiency.[1–3] A component efficiency drop of the order 2% may occur between takeoff and cruise conditions for large commercial transport engines and could be as large as 7% for smaller engines at higher altitude. An efficient means of of separation elimination/reduction is, therefore, crucial to improved turbine design. Because the large change in the Reynolds number from takeoff to cruise leads to a distinct change in the airfoil flow physics, a separation control strategy intended for cruise conditions will need to be carefully constructed so as to incur minimum impact/penalty at takeoff.

A complicating factor, but also a potential advantage in the quest for an efficient strategy, is the intricate interplay between separation and transition for the situation at hand. Volino[5] gives a comprehensive discussion of several recent studies on transition and separation under low-pressure-turbine conditions, among them one in the present facility.[6] Transition may begin before or after separation, depending on the Reynolds number and other flow conditions. If the transition occurs early in the boundary layer then separation may be reduced or completely eliminated. Transition in the shear layer of a separation bubble can lead to rapid reattachment. This suggests using control mechanisms to trigger and enhance early transition.

Gad-el-Hak[4] provides a review of various techniques for flow control in general and Volino[7] discusses recent studies on separation control under low-pressure-turbine conditions utilizing passive as well as active devices. As pointed out by Volino[7], passive devices optimized for separation control at low Reynolds numbers tend to increase losses at high Reynolds numbers. Active devices have the attractive feature that they can be utilized only in operational regimes where they are needed and when turned off would not affect the flow. The focus in the present paper is an experimental study[8,9] of active separation control using glow discharge plasma actuators.

Separation is induced on a flat plate installed in a closed-circuit wind tunnel by a shaped insert on the opposite wall. The flow conditions represent flow over the suction surface of a modern low-pressure-turbine airfoil ('Pak-B'). The Reynolds number, based on wetted plate length and nominal exit velocity, is varied from $50,000$ to $300,000$, covering cruise to takeoff conditions. Low (0.2%) and high (2.5%) free-stream turbulence intensities are set using passive grids. A spanwise-oriented phased-plasma-array actuator,[10] fabricated on a printed circuit board, is surface-flush-mounted upstream of the separation point and can provide forcing in a wide frequency range. Static surface pressure measurements and hot-wire anemometry of the base and controlled flows are performed and indicate that the glow-discharge plasma actuator is an effective device for separation control.

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[1] Mayle, R.E., 1991, "The Role of Laminar-Turbulent Transition in Gas Turbine Engines," *ASME J. of Turbomachinery* **113**, 509-537.

[2] Hourmouziadis, J., 1989, "Aerodynamic Design of Low Pressure Turbines," AGARD Lecture Series, 167.

[3] Sharma, O.P., Ni, R.H. and Tanrikut, S., 1994, "Unsteady Flow in Turbines," AGARD-LS-195, Paper No. 5.

[4] Gad-el-Hak, M., 2000, *Flow Control, Passive, Active, and Reactive Flow Management*, Cambridge Univ. Press, Cambridge.

[5] Volino, R. J., 2002, "Separated Flow Transition Under Simulated Low-Pressure Turbine Airfoil Conditions: Part 1—Mean Flow and Turbulence Statistics," *J. Turbomachinery* **124**, 645-655 (2002). Also ASME Paper 2002-GT-30236.

[6] Volino, R. J. and Hultgren, L. S., 2001, "Measurements in Separated and Transitional Boundary Layers Under Low-Pressure Turbine Airfoil Conditions," *J. Turbomachinery* **123**, 189-197. Also ASME Paper 2000-GT-0260.

[7] Volino, R. J., 2003, "Separation Control on Low-Pressure Turbine Airfoils Using Synthetic Vortex Generator Jets," ASME Paper 2003-GT-38729.

[8] Hultgren, L. S. and Ashpis, D. E., 2002, "Glow Discharge Plasma Active Control of Separation Control at Low Pressure Turbine Conditions," *Bull. Amer. Phys. Soc.* **47**, No. 10, 167.

[9] Hultgren, L. S. and Ashpis, D. E., 2003, "Demonstartion of Separation Delay with Glow-Discharge Plasma Actuators," AIAA Paper 2003-1025.

[10] Corke, T. C. and Matlis, E., 2000, "Phased Plasma Arrays for Unsteady Flow Control," AIAA Paper 2000-2323.

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Boundary-Layer Separation Control Under Low-Pressure-Turbine Conditions Using Glow-Discharge Plasma Actuators

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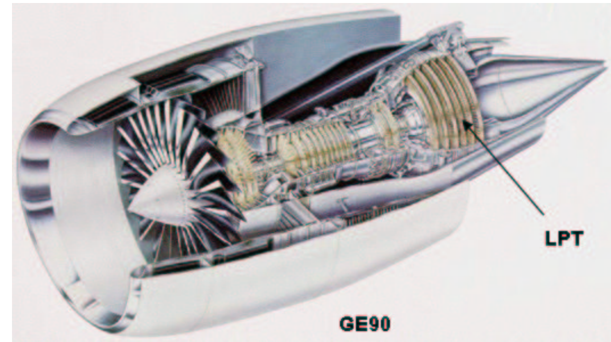
MOTIVATION



- Control of flow separation on low pressure turbine (LPT) airfoils

- Characteristics of flow in LPT airfoil passages:
  - ◇ low Reynolds number 25000-300000, exit Mach number ≈ 0.5
  - ◇ high free stream turbulence 0.5% to 10%
  - ◇ complex flow—transition, wakes, separation, etc
  - ◇ efficiency degradation between takeoff and cruise conditions due laminar separation on suction surface caused by decrease of Reynolds number with altitude (density effect)
- LPT is a good target for improvements
  - ◇ large diameter, many airfoils, many stages, heavy
  - ◇ large efficiency degradation between takeoff & cruise conditions (2 pts large commercial)
- Only so much can be accomplished by shape optimization
- Breakthrough technology is needed—ACTIVE FLOW CONTROL

STUDIES OF LPT AIRFOIL FLOW CONTROL

- Passive Flow Control
  - ◇ dimples (Lake et al 2000)
  - ◇ 2D tripps (Lake et al 2000, Volino 2002)
  - ◇ vortex generators (Volino 2000, van Treuren et al 2001)
- Active Flow Control
  - ◇ steady & pulsed vortex-generator jets (Bons 1999, Sondergaard et al 2000)
  - ◇ zero-net-mass vortex-generator jets (Volino DFD02)
  - ◇ glow-discharge plasma actuators (Corke et al DFD02, Reno03; Byerley et al Reno03) — both are steady-forcing experiments

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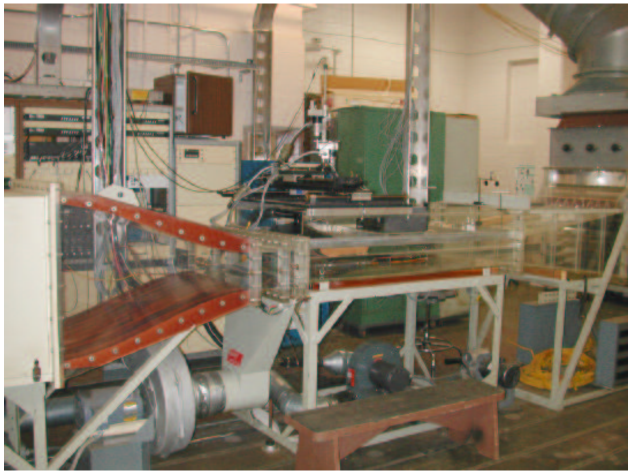
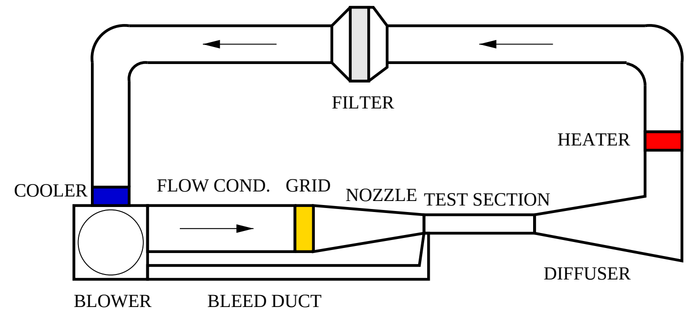
CW-7 FACILITY at NASA GRC

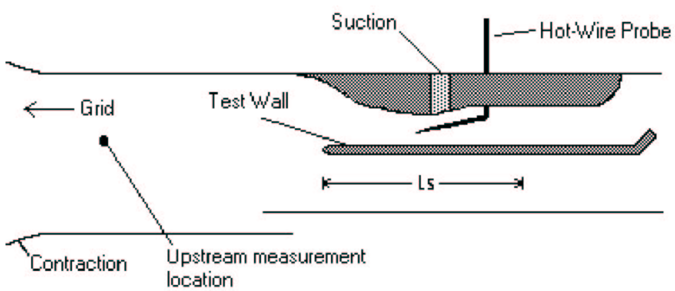


CW-7 FACILITY at NASA GRC



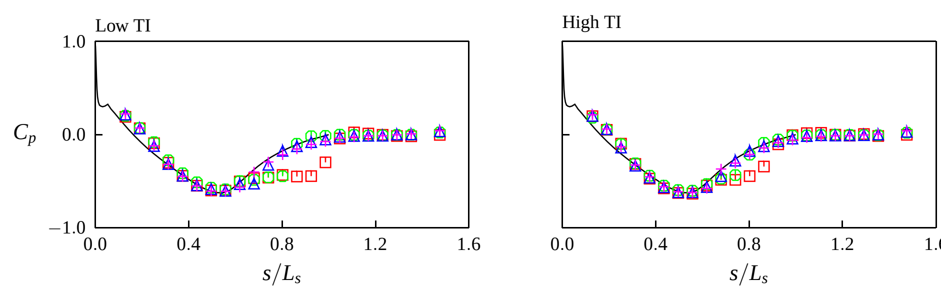
- Closed-loop wind tunnel with cooling/heating
  - ◇ bleed duct and heater not used

CW-7 TEST SECTION



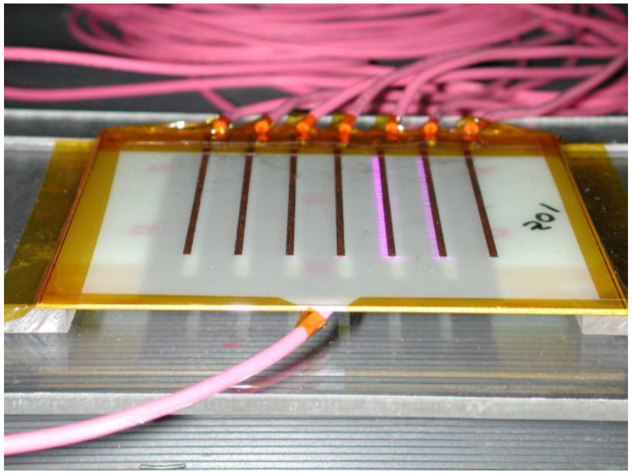
- Contoured upper wall in test section $\Rightarrow C_p$
- Flat plate simulating blade

STATIC PRESSURE DISTRIBUTIONS

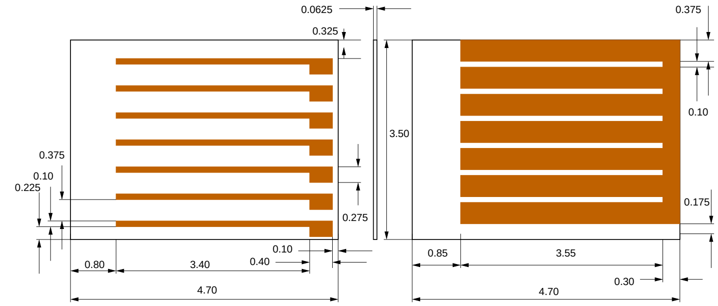


- $Re \equiv U_e L_s/\nu = 50000, 100000, 200000$, and 300000
- Nominal test-section freestream TI levels, low: 0.2%, high: 2.5%
- Scanivalve J-type multiplexer, Druck LPM 9381: ±0.1kPa, ±1kPa

NASA GRC ACTUATOR

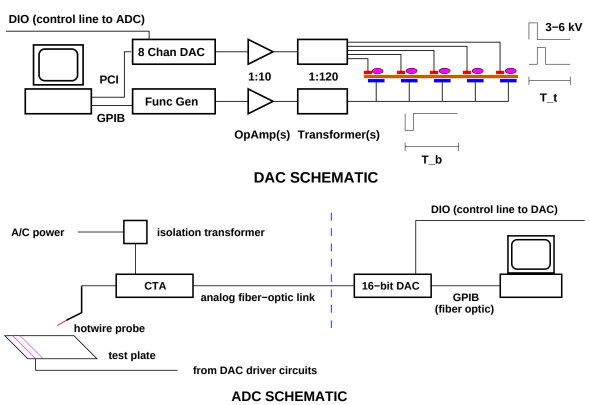


NASA GRC ACTUATOR



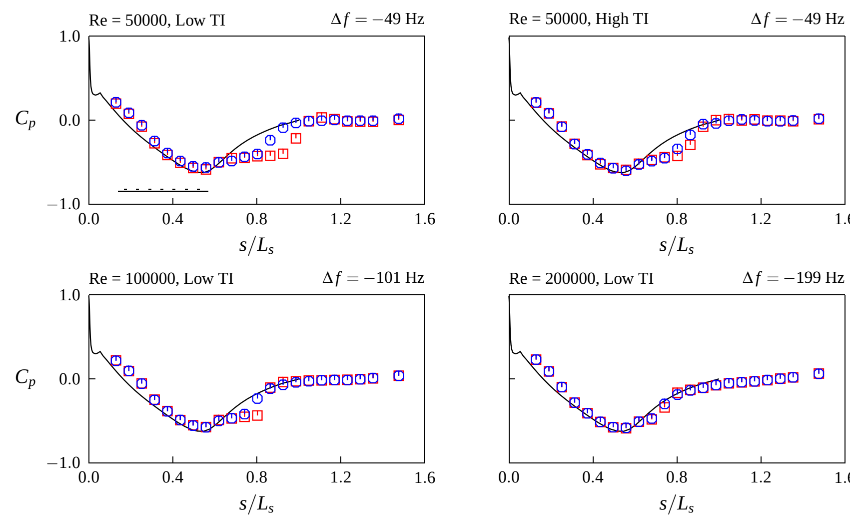
- Fabricated using printed circuit board technology
- Geometry an improvement of an early U. Notre Dame design

APPROACH



- Phased plasma array (Corke & Matlis 2000)

EFFECT OF ACTUATOR



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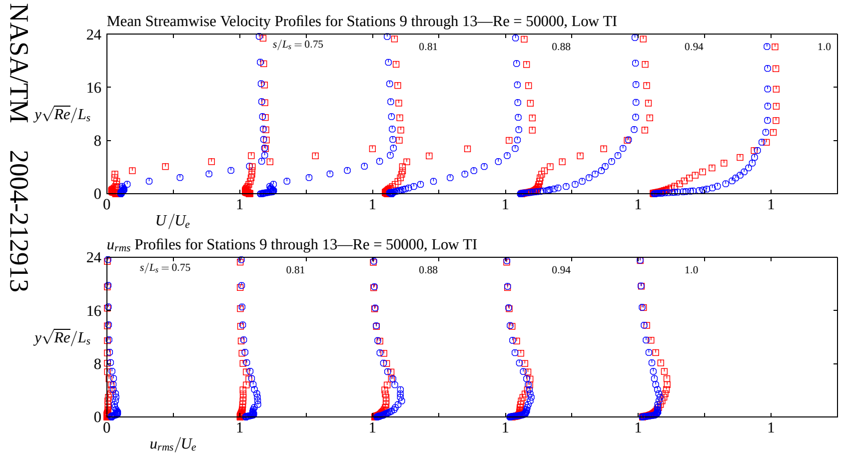
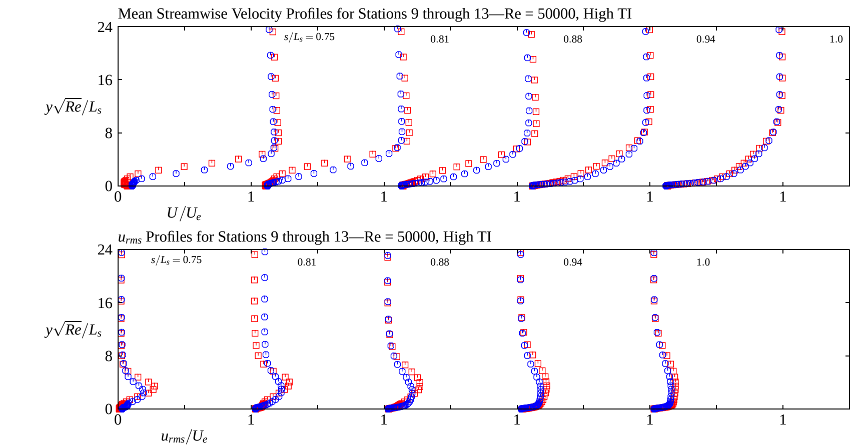
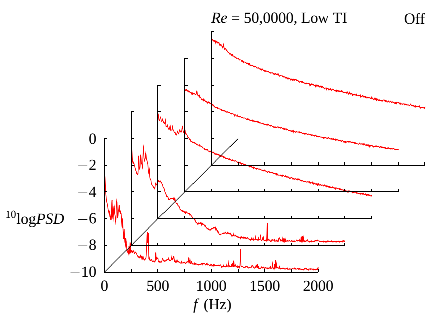
Re = 50000—Low TI

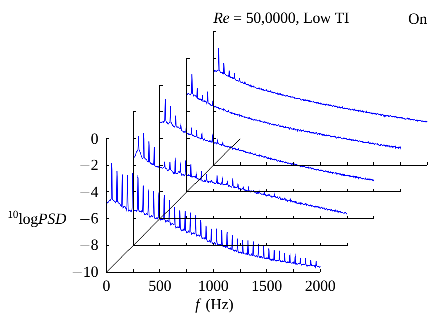


Re = 50000—High TI



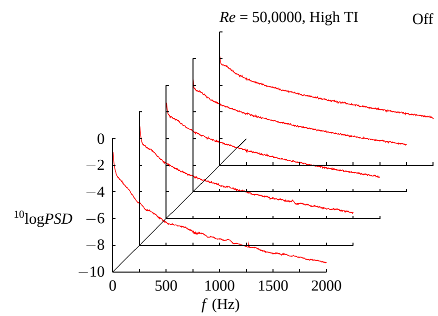
Re = 50000, Low TI—Power Spectral Density Evolution

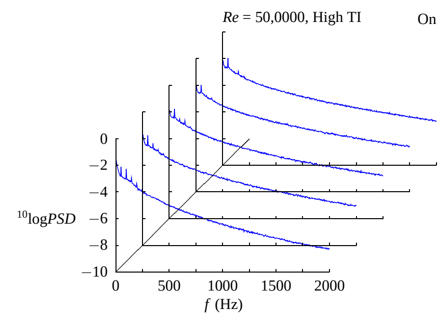




- Off: shear-layer instability—higher harmonics—transition—reattachment
- On: very late transitional—turbulence—reattachment
- Actuator promotes early transition in separated shear layer

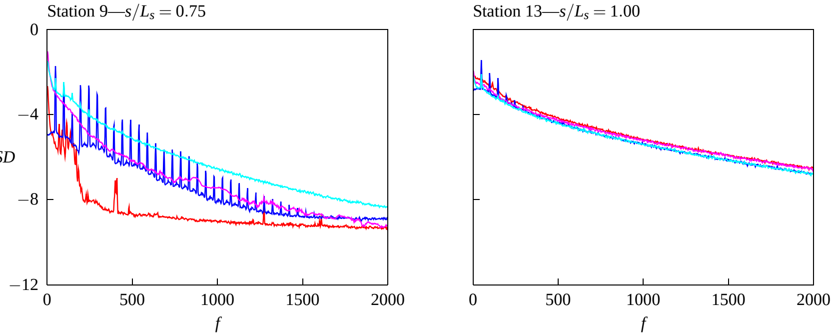
Re = 50000, High TI—Power Spectral Density Evolution





- Off: bypass transition—turbulence—reattachement
- On: transition process accelerated
- Limited further effects after transition to turbulence

Re=50000—POWER SPECTRAL DENSITY



- Shear-layer instability for low TI—bypass transition for high TI
- Spectra similar after transition/re-attachment
- Instability freq. range coincides with actuator observed effective range

SUMMARY

- Separation is a relevant issue in turbomachinery flow
- Experimental study carried out in GRC wind tunnel at LPT conditions
- Active flow control can eliminate/reduce separation
- Current actuator promotes early transition in separated shear layer
- Effective frequency range correlates with shear layer instability range
- Advantages of using glow-discharge plasma actuators:
  - can provide forcing in a wide frequency range
  - when turned off could be totally nonintrusive